

# Pulsars Tracing Black Holes in Globular Clusters

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**Abstract.** Results of precise measurements of the periods of pulsars discovered in the central regions of globular clusters are shown to be approaching the capabilities of testing the existence of a central black hole. For example, in the case of M 15 the available data on two pulsars PSR 2129+1210A and PSR 2129+1209D seem to exclude the existence of a black hole, the presence of which was instead supported by recent Hubble Space Telescope data on surface brightness profile (Yanny *et al.* 1994). The fluctuations of the gravitational field caused by the stars of the system are enough to explain the acceleration observed for both pulsars. In the case of the Galactic center, additional data are needed for similar definite conclusions.

**Key words:** Pulsars: general; individual – clusters: globular

## 1. Introduction

Hubble Space Telescope (HST) observations of globular clusters provide a unique possibility of revealing the nature of their central regions. Do globular clusters contain central black holes or are we dealing with purely stellar dynamical phenomena? The idea of black holes which might be situated at the centers of globular clusters has been seriously debated since the first identification of X-ray sources within globular clusters (Bahcall & Ostriker 1975, Silk & Arons 1975, Newell, Da Costa & Grindlay 1976). Ground based studies on surface brightness and velocity dispersion profiles were not accurate enough for model independent analysis of the problem (e.g. Dubath, Meylan & Mayor 1993, Meylan 1994). Recent HST observations of M 15 (Yanny *et al.* 1994), one of the most dense clusters, support the theoretically predicted star density slope (Bahcall & Wolf 1976) for stars in the presence of a central massive black hole and support the possibility that this black hole has a mass of  $M_{bh} \simeq 10^3 M_{\odot}$ . However, the observed surface brightness distribution can also be explained via a King model with core radius  $r_c = 2.2''$  (Phinney 1993, Gebhardt & Fischer 1995).

The aim of the present paper is to suggest the possibility of using millisecond pulsars as a trace of the central regions of globular clusters with the particular aim of revealing the existence of central black holes. Millisecond radio-pulsars were

discovered and intensively studied in recent years (see e.g. Taylor, Manchester & Lyne 1993).

Among the eight pulsars discovered in the globular cluster M 15, two, i.e. PSR 2129+1210A and PSR 2129+1209D (also known as PSR 2127+11A and PSR 2127+11D), are situated rather close (within  $1.1''$ ) to its center, i.e. inside 0.05 pc from the center, for the distance to M 15 of 10 kpc (Phinney 1993). The main characteristics of these pulsars are given in Table 1, together with two more pulsars in 47 Tucanae with negative  $\dot{P}$ .

Obviously, we are considering the case of M 15 Tucanae, not only because of the recent interpretation supporting the presence of a central black hole (Yanny *et al.* 1994), but also due to the more complete data available at present, both on pulsars and the cluster center.

## 2. P relation to the (3+1)-Geometry

The properties of the pulsars' periods  $P$  and of their time derivatives  $\dot{P}$  and the possibility of their accurate measurement have made pulsars a kind of unique cosmic clock. Along with this the present accuracy of the localization of pulsars within the globular cluster as well as the resolved centers of the latter, are approaching the values when the afore mentioned properties of the pulsars can become tracers of a central black hole and/or of the dynamical parameters of the cluster.

Indeed, the relation of the proper time interval  $\Delta\tau$  for a source located in the central symmetric gravitational field with the radial coordinate, yields:

$$\Delta\tau = \sqrt{g_{00}}\Delta t. \quad (1)$$

where  $g_{00} = (1 - r_g/r)$ ,  $r_g$  being the gravitational radius. From here, one can easily derive that a pulsar moving in the vicinity of a Schwarzschild black hole from the distance  $r_1$  to  $r_2$  within the time interval  $\Delta T$  will undergo the following apparent variation of period

$$\frac{\Delta P}{P} \simeq \frac{1}{2} \frac{r_g}{r} \frac{\Delta r}{r}, \quad (2)$$

with  $\Delta r \equiv r_1 - r_2 = v \Delta T$ ,  $v$  the pulsar's velocity,  $r$  the mean distance of the pulsar from the central black hole and  $\Delta r \ll r$ . Assuming  $v \simeq 15 \text{ km s}^{-1}$  we obtain the characteristic time scale for the given  $\Delta P/P$ :

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**Table 1.** Main parameters of two central pulsars in M15 (Taylor, Manchester & Lyne 1993) and two pulsars in 47 Tucanae (Robinson *et al.* 1995).

Name	R. A.	Dec.	$P$	$\dot{P}$	$d_{min}$	$d_{max}$
PSR J	(J2000)	(J2000)	(s)	( $10^{-17}$ )	(kpc)	(kpc)
2129+1210A	21:29:58.247	+12:10:01.30	0.1106647087715 ( $\pm 3$ )	-2.107 ( $\pm 3$ )	8.9	11.1
2129+1209D	21:29:58.274	+12:09:59.74	0.0048028043457 ( $\pm 3$ )	-1.75 ( $\pm 12$ )	8.9	11.1
0024-72C	00:23:50.343	-72:04:31.46	0.00575678001161 ( $\pm 1$ )	-0.00498 ( $\pm 1$ )	4.1	4.9
0024-72D	00:24:13.877	-72:04:43.82	0.00535757328590 ( $\pm 1$ )	-0.00028 ( $\pm 2$ )	4.1	4.9

$$\Delta T \simeq 3 \text{ yrs} \left( \frac{\Delta P/P}{10^{-12}} \right) \left( \frac{M_{bh}}{10^3 M_\odot} \right)^{-1} \quad (3)$$

for PSR 2129+1210A in M 15. This means that the measurements within the time scale (3) performed at any typical epoch have to lead to the change of the ratio  $\Delta P/P$  at least in the 12th digit. Here, the value of the pulsar velocity has been chosen to be equal to the stellar velocity dispersion as a minimum value following from stellar dynamical considerations; the higher will be the proper velocity of the pulsar - the shorter should be the time scale (3). The probable mass range of the central black hole in M15 is obtained by Yanny *et al.* (1994) based on the brightness profile:  $1 \times 10^3 M_\odot \leq M_{bh} \leq 3 \times 10^3 M_\odot$ . The corresponding gravitational radius of such a black hole is  $r_g = 2GM_{bh}/c^2 = 2'' \times 10^{-9} (M_{bh}/10^3 M_\odot)$ .

One can see, that the already observed stability, namely, up to the 12th digit, of  $P$  for the first pulsar (Table 1) enables us to exclude the existence of a black hole of mass within the mentioned interval.

A less restrictive limit is obtained by considering PSR 2129+1209D in M15: from the same equation (3) we obtain that it is possible to exclude the presence of a black hole of a mass greater than  $3 \times 10^3 M_\odot$ .

Note that black holes of smaller mass, i.e. of order of  $10^2 M_\odot$  (with numerical factor depending on the parameters of the star cluster), are also excluded by considerations of the precise localization in the center of the system (Bahcall & Wolf 1976, Gurzadyan 1982).

What can then be the reason for the negative  $\dot{P}$  for both pulsars? The fluctuations of the gravitational field of the stars in the system seem to be sufficient to cause this effect (Blandford, Romani & Applegate 1987, Nice & Thorsett 1992). Indeed, for the estimated star density  $n \sim 10^7 \text{ pc}^{-3}$  (Phinney & Sigurdsson 1991), the mean period of fluctuations of the force is  $n^{-1/3}/v \approx 3 \times 10^2 \text{ yrs}$ , where  $v \simeq 15 \text{ km s}^{-1}$  is the stellar velocity dispersion. If the increase of the velocity dispersion towards the center of the system measured since 1989 is confirmed, then this time scale can become even less. Correspondingly, the lower limit for the acceleration due to perturbations of the surrounding stars should be  $\dot{P}/P \simeq 3 \times 10^{-17} \text{ s}^{-1}$ , thus exceeding the observed acceleration parameters for both these pulsars (Table 1); hence, it should overwhelm the intrinsic spin-down of the pulsar.

Let us now briefly discuss another two pulsars with negative  $\dot{P}$  (see Table 1) in the globular cluster 47 Tucanae, PSR 0024-72C and PSR 0024-72D. The distance of these pulsars from the cluster center is 1.5 pc and 0.75 pc, respectively, i.e. much higher than the distance of PSR 2129+1210A and 2129+1209D from the center of M15. Therefore, no valuable constraint can be obtained in this case for the existence of a central black

hole. Instead, one can use the small value of their  $\dot{P}$  to derive a lower limit for the central mass density of 47 Tucanae. In fact, due to the mean field acceleration  $a_l$  of a pulsar along the line of sight, it must be (see e.g. Robinson *et al.* 1995)

$$\left| \frac{\dot{P}}{P} \right| < \left| \frac{a_l}{c} \right|. \quad (4)$$

By using a King model for the mass distribution of the cluster one has, from equation (4),

$$\rho_{min}(0) = \left| \frac{9 c r}{4\pi G r_c^2} \frac{\dot{P}}{P} \right| \sim 8 \times 10^4 M_\odot \text{ pc}^{-3}, \quad (5)$$

where  $r$  is the distance of the pulsar from the cluster's center and  $r_c \simeq 0.5 \text{ pc}$  is the King *core* radius (Calzetti *et al.* 1993).

Concerning the situation in the Galactic center, there are at least two pulsars located presumably in its vicinity, i.e. PSR 1748-2446A and PSR 1749-3002 (also called PSR 1744-24A and PSR 1746-30), whose main characteristics are given in Table 2. One of them (PSR 1748-2446A) is located at least 210 pc from the Galactic center (taking the distance to the Galactic center to be 10 kpc though the real distance can be less (Genzel & Townes 1987)), so that  $r_g/r \simeq 5 \times 10^{-10}$  for the mass of a central black hole  $\sim 10^6 M_\odot$ . The available accuracy of measurement of  $P$  for that pulsar is again of the order of  $10^{-10}$ , so that it is still not possible to derive any definite conclusion on the existence of a black hole in the center of the galaxy.

### 3. Discussion and predictions

The accuracy of HST data on the globular cluster centers along with the measurements of the parameters of radio-pulsars in those systems can already provide the possibility of studying the parameters of the stellar systems via the properties of the pulsars. In particular, these data can lead to model independent conclusions on the presence of black holes. In the example of M 15 we have seen that the measured parameters of PSR 2129+1210A (located within 1.1'' from the center), seems to exclude the possibility of the existence of a black hole of mass  $\sim 10^3 M_\odot$ , whose existence was instead required by the interpretation of the recent HST photometric data (Yanny *et al.* 1994). Since a black hole of a lower mass is excluded (Bahcall & Wolf 1976, Gurzadyan 1982), the existence of a black hole in the center of this cluster seems to be excluded at all.

Note, that in future studies, aside from problems associated with the measurements of the pulsar parameters, one has to consider contribution of various effects which can lead to

**Table 2.** Main parameters of two pulsars close to the Galactic center (Taylor, Manchester & Lyne 1993).

Name	R. A.	Dec.	$P$	$\dot{P}$	$d_{min}$	$d_{max}$
PSR J	(J2000)	(J2000)	(s)	( $10^{-17}$ )	(kpc)	(kpc)
1748-2446A	17:48:02.2534	-24 : 46 : 37.7	0.01156314838966 ( $\pm 2$ )	$-1.9 \times 10^{-3}$ ( $\pm 2$ )	6.4	7.8
1749-3002	17:49:13.48	-30 : 02 : 34	0.60987235659 ( $\pm 3$ )	787.1 ( $\pm 2$ )	9.11	
					(mean value)	

errors in the estimation of distances of pulsars from the center of the clusters. Then, it will be necessary to take into account the accuracies in the alignment of the ephemerides dynamical frame with the optical one, the accurate definition of the cluster center, e.g. via the luminosity profile or via the dynamical properties (cf Calzetti *et al.* 1993), and so on. However, the conclusion made above for M 15 is not altered even if the pulsar position with respect to the cluster center is known with an error as large as  $0.5''$ ; in reality errors are expected to be much less (Meylan 1994).

The conditions within the core of M 15 seem to provide also the possibility of explaining the acceleration observed for both pulsars as due to the field perturbations caused by the surrounding stars. This allows us to make the *first prediction* concerning the single pulsars, i.e. non-members of binary systems: *the acceleration of pulsars should be observed with essentially higher probability in globular clusters and in the Galactic center, than, say, in the disk of the Galaxy.*

The effect of perturbations caused by the surrounding stars, in principle, can be empirically distinguished from the perturbation caused by the regular field of the cluster core considered by Wolcszan *et al.* (1989), Phinney (1991), Nice & Thorsett (1992). The point is that the role of the core should become more important towards the boundary of the cluster and will tend to zero approaching the center, while the stellar contribution, vice versa, will increase towards the center.

This leads to our *second prediction*: *accelerated pulsars should be situated mainly in the central regions of the globular clusters, rather than in their peripheral regions.* Obviously, some probability remains of the pulsars being perturbed by a chance encounter with a star. The projection effects should also not be neglected when considering the corresponding probabilities. Moreover the existence of anomalously accelerated pulsars with  $\dot{P}$  positive not fitting the typical magnetic field action, also should be expected in the central region of globular clusters, due to the same effect of stellar perturbations.

Concerning the role of stellar perturbations on pulsars one can predict one more effect: the change of the orientation of their rotational axes. The effect of regular or chaotic variation of the rotational axes is known for the case of the planets (see, Laskar 1994; Laskar 1995 and references therein) and can be represented as a problem of a system with perturbed Hamiltonian:

$$H(I, \varphi, \epsilon) = H_0(I) + \epsilon H_1(I, \varphi, \epsilon). \quad (6)$$

Since the corresponding problem is integrable only in the case of a single periodic perturbation term (Colombo, 1966), one can conclude that stellar perturbations in the form represented by Chandrasekhar and von Neumann (1943) have to lead to chaotic variations of the pulsar axes.

Thus, pulsars cannot avoid this effect, even for the lowest values of their oblateness. The numerical estimation of the

obliquity variation, time scales, etc., can vary within extremely broad ranges, since it crucially (non-linearly) depends upon numerous parameters of the problem; the corresponding modelling is a topic of comprehensive studies and is out of the scope of our paper. We only note that empirical studies can themselves provide information on this effect as well.

Our *third prediction* therefore reads: *pulsars located in the central regions of globular clusters, in principle, should undergo chaotic variations of their spin axes and, as a result, can reveal spontaneous appearances and disappearances during their observations.*

These examples indicate:

- a) the existence of a special subclass of pulsars, i.e. those situated in globular clusters with properties different from those situated in the Galactic disk or in the halo;
- b) the importance of the search of pulsars in the central regions of globular clusters and of the Galaxy in revealing the dynamical structure of those systems, including the presence of massive black holes.

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